

# Probing Topcolor-Assisted Technicolor from Like-sign Top Pair Production at LHC

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The topcolor-assisted technicolor (TC2) theory predicts tree-level flavor-changing neutral-current (FCNC) top quark Yukawa couplings with top-pions. Such FCNC interactions will induce like-sign top quark pair productions at CERN Large Hadron Collider (LHC). While these rare productions are far below the observable level in the Standard Model and other popular new physics models such as the Minimal Supersymmetric Model, we find that in a sound part of parameter space the TC2 model can enhance the production cross sections to several tens of fb and thus may be observable at the LHC due to rather low backgrounds. Searching for these productions at the LHC will serve as an excellent probe for the TC2 model.

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## I. INTRODUCTION

Top quark physics [1] will be intensively studied in the coming years. The Fermilab Tevatron Collider and the CERN Large Hadron Collider (LHC) will copiously produce top quarks and allow to scrutinize top quark properties. Any new physics related to top quark will be uncovered or stringently constrained [2]. One striking property of top quark in the Standard Model (SM) is its extremely weak flavor-changing neutral-current (FCNC) interactions due to the GIM mechanism: they are absent at tree-level and highly suppressed at loop-level [3]. By contrast, the extensions of the SM often inevitably predict much larger FCNC interactions for top quark. Therefore, the study of top quark FCNC processes will serve as a sensitive test of the SM and a powerful probe of new physics.

In the extensions of the SM, the top quark FCNC interactions may be enhanced through two ways. One is that at loop-level the GIM mechanism does not work so well as in the SM since new particles enter the loops to mediate top quark FCNC transitions. The other is that some models naturally predict tree-level top quark FCNC Yukawa couplings with scalar fields, which is in contrast with the SM where the generation of fermion masses is realized by simply introducing Yukawa couplings with only one Higgs doublet and, as a result, the Yukawa couplings can be diagonalized simultaneously with the fermion mass matrices. The enhanced top quark FCNC interactions will lead to various possibly observable FCNC processes at colliders, such as the FCNC decays [4–6] and the top-charm associated productions [7,8]. In addition, they can also induce the like-sign top pair productions at the LHC. Unlike top-charm associated productions, these like-sign top pair productions are free from huge QCD background  $W + jets$  and also from  $t\bar{t}$  background [9]. Due to rather low backgrounds [10], such productions will be an excellent probe for top quark FCNC interactions [11].

In this article, we study the possibility of using the like-sign top pair productions at the LHC to probe the topcolor-assisted technicolor (TC2) theory [12,13]. This theory, which combines the fancy idea of technicolor [14] with top quark condensation [15], has not yet been excluded by experiments and remains a typical candidate of new physics in the direction of dynamical electroweak symmetry breaking (EWSB). A remarkable feature of this theory is that it predicts tree-level FCNC Yukawa interactions for top quark since top quark is singled out for condensation to generate the main part of its mass [16,17]. Such tree-level FCNC interactions are likely to induce sizable like-sign top pair productions at the LHC. Since these rare productions are far below the observable level in the SM and other popular new physics models like supersymmetry (we will discuss and estimate later), the observation/unobservation of these productions will strongly favor/disfavor the TC2 theory.

This paper is organized as follows. In Section II, we first briefly introduce the TC2 theory and then recapitulate the current theoretical and experimental constraints on the parameters of this theory. In Section III, we calculate various like-sign top pair productions at the LHC induced by top quark FCNC interactions in the TC2 theory and discuss their observability. We also discuss about the predictions of other popular new physics models. Finally in Section IV we give the conclusion.

## II. TOPCOLOR-ASSISTED TECHNICOLOR

The TC2 theory [12,13] introduces two strongly interacting sectors, with one sector (topcolor interaction) generating the large top quark mass and partially contributing to EWSB while the other sector (technicolor interaction) responsible for the bulk of EWSB and the generation of light fermion masses. At the EWSB scale, it predicts the existence of two groups of composite scalars from topcolor and technicolor condensations, respectively [12,13,15]. In the linear realization, the scalars of our interest can be arranged into two  $SU(2)$  doublets, namely  $\Phi_{top}$  and  $\Phi_{TC}$  [15,18,19], which are analogous to the Higgs fields in a special two-Higgs-doublet model [20]. The doublet  $\Phi_{top}$  from topcolor condensation couples only to the third-generation quarks. Its main task is to generate the large top quark mass. It can also generate a sound part of bottom quark mass indirectly via instanton effect [12]. Since a small value of the top-pion decay constant  $F_t$  (the vev of the doublet  $\Phi_{top}$ ) is theoretically favored (see below), this doublet must couple strongly to top quark in order to generate the expected top quark mass. The other doublet  $\Phi_{TC}$ , which is technicolor condensate, is mainly responsible for EWSB and light fermion masses. It also contributes a small portion to the third-generation quark masses. Because its vev  $v_{TC}$  is generally comparable with  $v_W$ , its Yukawa couplings with all fermions are small. The low-energy effective Lagrangian can be written as [19]

$$\mathcal{L} = |D_\mu \Phi_{TC}|^2 + |D_\mu \Phi_{top}|^2 - \left( \sum_{i,j=1}^3 \lambda_{ij}^U \bar{Q}_{Li} \Phi_{TC} U_{Rj} + \sum_{i,j=1}^3 \lambda_{ij}^D \bar{Q}_{Li} \tilde{\Phi}_{TC} D_{Rj} + Y_t \bar{\Psi}_L \Phi_{top} t_R + h.c. \right) + \dots \quad (1)$$

where  $D_\mu = \partial_\mu + ig' \frac{Y}{2} B_\mu + ig \frac{\tau_t}{2} W_\mu^i$ ,  $Q_{Li}$  denotes the left-handed quark doublet,  $U_{Rj}$  and  $D_{Rj}$  are right-handed quarks,  $\Psi_L$  is the left-handed top-bottom doublet,  $\tilde{\Phi}_{TC}$  is the conjugate of  $\Phi_{TC}$ , and  $\lambda_{ij}^{U,D}$  and  $Y_t$  are Yukawa coupling constants satisfying  $\lambda_{ij}^{U,D} \ll Y_t$ . The two  $SU(2)$  doublets take the form

$$\Phi_{TC} = \begin{pmatrix} v_{TC} + (H_{TC}^0 + i\Pi_{TC}^0)/\sqrt{2} \\ \Pi_{TC}^- \end{pmatrix}, \quad (2)$$

$$\Phi_{top} = \begin{pmatrix} F_t + (H_{top}^0 + i\Pi_{top}^0)/\sqrt{2} \\ \Pi_{top}^- \end{pmatrix}. \quad (3)$$

We can rotate the two doublets into  $\Phi_{1,2}$  such that  $\langle \Phi_1 \rangle = \sqrt{v_{TC}^2 + F_t^2} = v_w$  and  $\langle \Phi_2 \rangle = 0$

$$\Phi_1 = (\cos \beta \Phi_{TC} + \sin \beta \Phi_{top}) = \begin{pmatrix} v_w + (H_1^0 + iG^0)/\sqrt{2} \\ G^- \end{pmatrix}, \quad (4)$$

$$\Phi_2 = (-\sin \beta \Phi_{TC} + \cos \beta \Phi_{top}) = \begin{pmatrix} (H_2^0 + iA^0)/\sqrt{2} \\ H^- \end{pmatrix}, \quad (5)$$

where  $\tan \beta = F_t/v_{TC}$ . Then the Lagrangian can be rewritten as

$$\begin{aligned} \mathcal{L} = & |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2 - \left( \sum_{i,j=1}^3 \lambda_{ij}^U \bar{Q}_{Li} \Phi_1 U_{Rj} + \sum_{i,j=1}^3 \lambda_{ij}^D \frac{\sqrt{v_w^2 - F_t^2}}{v_w} \bar{Q}_{Li} \tilde{\Phi}_1 D_{Rj} \right. \\ & \left. - \sum_{i,j=1}^3 \lambda_{ij}^D \frac{F_t}{v_w} \bar{Q}_{Li} \tilde{\Phi}_2 D_{Rj} - \sum_{i,j=1}^3 \lambda_{ij}^U \frac{F_t}{v_w} \bar{Q}_{Li} \Phi_2 U_{Rj} + Y_t \frac{\sqrt{v_w^2 - F_t^2}}{v_w} \bar{\Psi}_L \Phi_2 t_R + h.c. \right) + \dots \end{aligned} \quad (6)$$

where  $\lambda_{ij}^U = \lambda_{ij}^U \cos \beta + Y_t \sin \beta \delta_{i3} \delta_{j3}$ . In this new basis,  $G^\pm$  and  $G^0$  are Goldstone bosons while the pseudoscalar  $A^0$ , the charged scalar  $H^\pm$  and the CP-even scalars  $H_{1,2}^0$  are physical Higgs bosons. It is obvious that  $H_1^0$  plays the role of the "standard" Higgs boson with flavor diagonal couplings and  $H_2^0$  decouples from the SM vector bosons but has strong coupling only with top quark. In our following analysis, we will adopt the same notations as in the literature, i.e., using top-Higgs  $h_t^0$ , top-pions  $\pi_t^{0,\pm}$  to denote  $H_2^0$ ,  $A^0$  and  $H^\pm$ , respectively.

In Eq.(6), the rotation of quarks into their mass eigenstates will induce FCNC Yukawa interactions from the  $\Phi_2$  couplings<sup>1</sup>. Since  $\lambda_{ij}^{U,D} \ll Y_t$ , the FCNC couplings from  $\lambda_{ij}^U$  and  $\lambda_{ij}^D$  can be safely neglected. Because  $Y_t = (1-\epsilon)m_t/F_t$

<sup>1</sup>Just like the Higgs field in the SM,  $\Phi_1$  terms give no FCNC couplings since they are diagonalized simultaneously with the fermion mass matrices.

( $\epsilon$  denoting the fraction of technicolor contribution to the top quark mass) is quite large (about  $2 \sim 3$ ) and the mixing between  $c_R$  and  $t_R$  can be naturally as large as 30% [16], the FCNC coupling from the  $Y_t$  term may be sizable and thus may have significant phenomenological consequence. The FCNC couplings from this term are given by

$$\mathcal{L}_{FCNC} = \frac{(1-\epsilon)m_t}{\sqrt{2}F_t} \frac{\sqrt{v_w^2 - F_t^2}}{v_w} \left( iK_{UL}^{tt*} K_{UR}^{tt} \bar{t}_L t_R \pi_t^0 + \sqrt{2} K_{UR}^{tt*} K_{DL}^{bb} \bar{t}_R b_L \pi_t^- + iK_{UL}^{tt*} K_{UR}^{tc} \bar{t}_L c_R \pi_t^0 + \sqrt{2} K_{UR}^{tc*} K_{DL}^{bb} \bar{c}_R b_L \pi_t^- + K_{UL}^{tt*} K_{UR}^{tt} \bar{t}_L t_R h_t^0 + K_{UL}^{tt*} K_{UR}^{tc} \bar{t}_L c_R h_t^0 + h.c. \right), \quad (7)$$

where  $K_{UL}$ ,  $K_{DL}$  and  $K_{UR}$  are the rotation matrices that transform the weak eigenstates of left-handed up-type, down-type and right-handed up-type quarks to their mass eigenstates, respectively. According to the analysis of [16], their favored values are given by

$$K_{UL}^{tt} \simeq K_{DL}^{bb} \simeq 1, \quad K_{UR}^{tt} \simeq \frac{m'_t}{m_t} = 1 - \epsilon, \quad K_{UR}^{tc} \leq \sqrt{1 - (K_{UR}^{tt})^2} = \sqrt{2\epsilon - \epsilon^2}, \quad (8)$$

with  $m'_t$  denoting the topcolor contribution to the top quark mass. In Eq.(7) we neglected the mixing between up quark and top quark.

Now we recapitulate the theoretical and experimental constraints on the relevant parameters.

- (1) About the  $\epsilon$  parameter. In the TC2 model,  $\epsilon$  parameterizes the portion of the extended-technicolor (ETC) contribution to the top quark mass. The bare value of  $\epsilon$  is generated at the ETC scale, and subject to very large radiative enhancement from the topcolor and  $U(1)_{Y_1}$  by a factor of order 10 when evolving down to the weak scale [12]. This  $\epsilon$  can induce a nonzero top-pion mass (proportional to  $\sqrt{\epsilon}$ ) [21] and thus ameliorate the problem of having dangerously light scalars. Numerical analysis shows that, with reasonable choice of other input parameters,  $\epsilon$  of order  $10^{-2} \sim 10^{-1}$  may induce top-pions as massive as the top quark [12]. Indirect phenomenological constraints on  $\epsilon$  come from low energy flavor-changing processes such as  $b \rightarrow s\gamma$  [22]. However, these constraints are very weak. From the theoretical point of view,  $\epsilon$  with value from 0.01 to 0.1 is favored. Since a large  $\epsilon$  can slightly suppress the FCNC Yukawa couplings, we fix conservatively  $\epsilon = 0.1$  throughout this paper.
- (2) The parameter  $K_{UR}^{tc}$  is upper bounded by the unitary relation  $K_{UR}^{tc} \leq \sqrt{1 - (K_{UR}^{tt})^2} = \sqrt{2\epsilon - \epsilon^2}$ . For a  $\epsilon$  value smaller than 0.1, this corresponds to  $K_{UR}^{tc} < 0.43$ . In our analysis, we will treat  $K_{UR}^{tc}$  as a free parameter.
- (3) About the top-pion decay constant  $F_t$ , the Pagels-Stokar formula [23] gives an expression in terms of the number of quark color  $N_c$ , the top quark mass, and the scale  $\Lambda$  at which the condensation occurs:

$$F_t^2 = \frac{N_c}{16\pi^2} m_t^2 \ln \frac{\Lambda^2}{m_t^2}. \quad (9)$$

From this formula, one can infer that, if  $t\bar{t}$  condensation is fully responsible for EWSB, i.e.  $F_t \simeq v_w \equiv v/\sqrt{2} = 174$  GeV, then  $\Lambda$  is about  $10^{13} \sim 10^{14}$  GeV. Such a large value is less attractive since by the original idea of technicolor [14], one expects new physics scale should not be far higher than the weak scale. On the other hand, if one believes that new physics exists at TeV scale, i.e.  $\Lambda \sim 1$  TeV, then  $F_t \sim 50$  GeV, which means that  $t\bar{t}$  condensation alone cannot be wholly responsible for EWSB and to break electroweak symmetry needs the joint effort of topcolor and other interactions like technicolor. By the way, Eq.(9) should be understood as only a rough guide, and  $F_t$  may in fact be somewhat lower or higher, say in the range  $40 \sim 70$  GeV. Allowing  $F_t$  to vary over this range does not qualitatively change our conclusion, and, therefore, we use the value  $F_t = 50$  GeV for illustration in our numerical analysis.

- (4) About the mass bounds for top-pions and top-Higgs. On the theoretical side, some estimates have been done. The mass splitting between the neutral top-pion and the charged top-pion should be small since it comes only from the electroweak interactions [24]. Ref. [12] has estimated the mass of top-pions using quark loop approximation and showed that  $m_{\pi_t}$  is allowed to be a few hundred GeV in a reasonable parameter space. Like Eq.(9), such estimations can only be regarded as a rough guide and the precise values of top-pion masses can be determined only by future experiments. The mass of the top-Higgs  $h_t^0$  can be estimated in the Nambu-Jona-Lasinio (NJL) model in the large  $N_c$  approximation and is found to be about  $2m_t$  [15,17]. This estimation is also rather crude and the mass below the  $t\bar{t}$  threshold is quite possible in a variety of scenarios [25]. On the experimental side, current experiments have restricted the mass of the charged top-pion. For example, the

absence of  $t \rightarrow \pi_t^+ b$  implies that  $m_{\pi_t^+} > 165$  GeV [26] and  $R_b$  analysis yields  $m_{\pi_t^+} > 220$  GeV [27,28]. For the neutral top-pion and top-Higgs, the experimental restrictions on them are rather weak. (Of course, considering theoretically that the mass splitting between the neutral and charged top-pions is small, the  $R_b$  bound on the charged top-pion mass should be applicable to the neutral top-pion masses.) The current bound on techni-pions [29] does not apply here since the properties of top-pion are quite different from those of techni-pions. The direct search for the neutral top-pion (top-Higgs) via  $pp$ (or  $p\bar{p}$ )  $\rightarrow t\bar{t}\pi_t^0(h_t^0)$  with  $\pi_t^0(h_t^0) \rightarrow b\bar{b}$  was proven to be hopeless at Tevatron for the top-pion (top-Higgs) heavier than 135 GeV [19]. The single production of  $\pi_t^0$  ( $h_t^0$ ) at Tevatron with  $\pi_t^0$  ( $h_t^0$ ) mainly decaying to  $t\bar{c}$  may shed some light on detecting top-pion (top-Higgs) [17], but the potential for the detection is limited by the value of  $K_{UR}^{tc}$  and the detailed background analysis is absent now. Anyhow, these mass bounds will be greatly tightened at the upcoming LHC [7,16,19]. Combining the above theoretical and experimental bounds, we in our discussion will assume

$$m_{h_t^0} > 135 \text{ GeV} \quad m_{\pi_t^0} = m_{\pi_t^+} \equiv m_{\pi_t} > 220 \text{ GeV}. \quad (10)$$

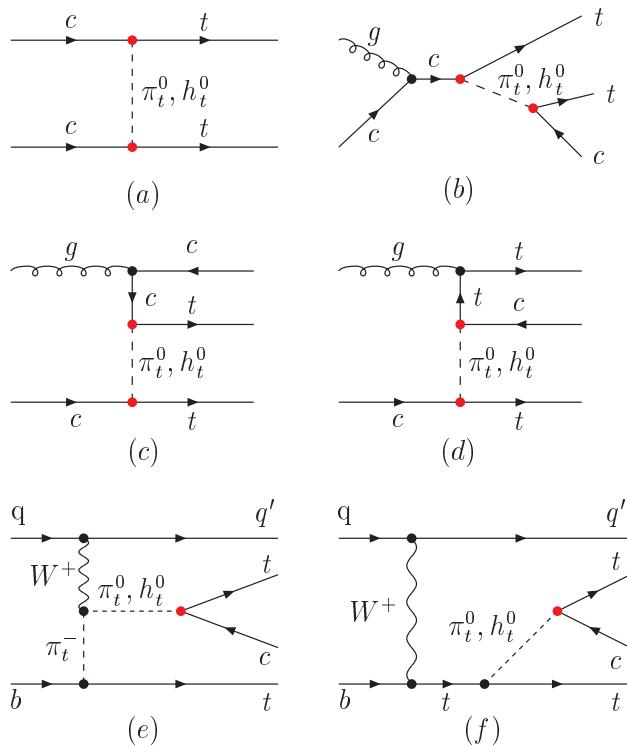


FIG. 1. Feynman diagrams for like-sign top pair productions induced by the FCNC Yukawa interactions in the TC2 model.

### III. LIKE-SIGN TOP PAIR PRODUCTION AT LHC

Due to the existence of the top quark FCNC Yukawa interactions in Eq.(7), the like-sign top pair productions can proceed through various parton processes at the LHC, as shown in Fig.1. Since the signals of these processes as well as their corresponding backgrounds are different, we will analyze these processes separately. Throughout this paper, we take  $m_t = 178$  GeV [30],  $m_w = 80.448$  GeV [29],  $\alpha_s(m_z) = 0.118$  and neglect bottom quark mass as well as charm quark mass. We used CTEQ6L [31] parton distribution functions with scale  $\mu = 2m_t$ .

#### A. $tt$ production at the LHC

In the TC2 model,  $pp \rightarrow tt + X$  proceeds through the parton process  $cc \rightarrow tt$  by exchanging a neutral top-pion or top-Higgs, as shown in Fig.1 (a). This process has two characters. One is that its cross section is proportional to

$(K_{UR}^{tc})^4$  in all the parameter space, and thus very sensitive to  $K_{UR}^{tc}$ . The other is that the top-pion diagrams and the top-Higgs diagrams interfere destructively and such destructive effect is significant for degenerate top-pion and top-Higgs masses. This feature is illustrated in Fig.2 for three representative values of  $m_{h_t}$ . For a light top-Higgs with  $m_{h_t} = 160$  GeV, the increase of the cross section as top-pion becomes heavier is due to the weakening cancellation effect. For a moderate top-Higgs with  $m_{h_t} = 300$  GeV, the dip of the cross section as  $m_{\pi_t}$  approaches  $m_{h_t}$  is a direct reflection of the cancellation effect. For a heavy top-Higgs  $m_{h_t} = 1000$  GeV, the top-Higgs contribution is strongly suppressed relative to the top-pion contribution and the total cross section is dominated by the top-pion contribution. As a result, the total cross section decreases monotonously as the top-pions get heavier, showing the decoupling effects.

Note that in Fig.2 we fix  $K_{UR}^{tc} = 0.4$  and the charge conjugate production  $pp \rightarrow \bar{t}t + X$  is also taken into account. The cross section for an arbitrary  $K_{UR}^{tc}$  value can be obtained by scaling the result of Fig.2 by a factor of  $(K_{UR}^{tc}/0.4)^4$ . So one can infer that even for  $K_{UR}^{tc} = 0.1$ , the cross section can still reach the level of several fb in a vast parameter space.

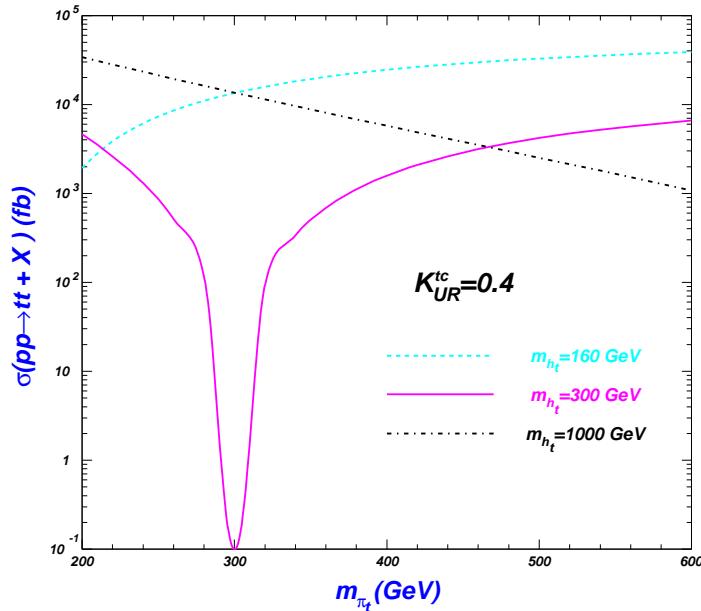


FIG. 2. Cross section of  $pp \rightarrow \bar{t}t + X$  at the LHC as a function of  $m_{\pi_t}$ .

Now we discuss the observability of the production  $pp \rightarrow \bar{t}t + X$  and its charge conjugate production channel. The semileptonical decay of both top (or anti-top) quarks give rise to a signal of like-sign dilepton plus two b-jets, i.e.,  $\ell^\pm \ell^\pm + 2$  b-jets ( $\ell = e, \mu$ ). The major backgrounds are from the production of  $t\bar{t}W^\pm$  (when the extra jets or leptons in the decay miss detection) and  $W^\pm q'W^\pm q'$  (when the two light quarks are misidentified as b-jets). Their corresponding rates are found to be [11,32,33]

$$\sigma(t\bar{t}W^+) = 0.21 \text{ pb}, \quad \sigma(t\bar{t}W^-) = 0.1 \text{ pb}, \quad (11)$$

$$\sigma(W^+ q' W^+ q') = 0.5 \text{ pb}, \quad \sigma(W^- q' W^- q') = 0.23 \text{ pb}. \quad (12)$$

To effectively suppress the backgrounds and at the same time not to hurt the signal too much, we search for the events with two like-sign leptons plus exactly two jets in which at least one is required to be a b-jet. Two-jets requirement can efficiently suppress  $t\bar{t}W$  background and one b-jet requirement can eliminate most  $WWqq$  background [10]. As a result, the background can be suppressed by one order. The  $S/B$  ratio can be further enhanced by imposing suitable kinematic cuts. From the analysis of Ref. [10], one may infer that by assuming 60% b-tagging efficiency <sup>2</sup>,

<sup>2</sup>In Ref. [10] a rather low b-tagging efficiency (36%) was taken and thus more signal events were cut out.

the background can be reduced to 6 events for  $100\text{fb}^{-1}$  integrated luminosity, at the cost of a reduction of 86% to the signal. So, for an integrated luminosity  $100\text{ fb}^{-1}$ ,  $\sigma(pp \rightarrow tt + X)$  larger than 10 fb may be observable at the LHC.

Note that in the TC2 theory there may exist other sources of FCNC which may contribute to  $cc \rightarrow tt$ . For example, the TC2 theory predicts a new gauge boson  $Z'$ , which can also mediate flavor-changing interactions [12]. However, electroweak data constrained  $Z'$  to be heavier than several TeV [34], and thus the effects of  $Z'$  are negligibly small.

### B. $tt\bar{c}$ production at the LHC

In the TC2 model the production  $pp \rightarrow tt\bar{c} + X$  proceeds through the patron process  $cg \rightarrow tt\bar{c}$ , as shown in Fig.1 (b,c,d). Like the process  $cc \rightarrow tt$ , top-pion diagrams and top-Higgs diagrams interfere destructively. Since top-pion and top-Higgs may be produced on-shell in this process, as shown in Fig.1 (b), we need to know their total widths. The possible decay channels of top-pion (top-Higgs) are

$$\pi_t^0(h_t) \rightarrow t\bar{t}, t\bar{c}, \bar{t}c, b\bar{b}, WW, ZZ, \gamma Z, gg, \gamma\gamma \quad (13)$$

For  $m_t < m_{\pi_t^0, h_t} < 2m_t$ , the process can be approximated as the direct production of top-pion (top-Higgs) followed by their decay to  $t\bar{c}$ . Since the last five decay modes in Eq.(13) occur only at loop-level, a moderate  $K_{UR}^{tc}$  will make  $t\bar{c}$  channel the dominant decay mode of top-pion (top-Higgs). So in the region  $m_t < m_{\pi_t^0, h_t} < 2m_t$ , the cross section is proportional to the square of  $K_{UR}^{tc}$ , less sensitive to  $K_{UR}^{tc}$  than in other parameter regions where the cross section is proportional to  $(K_{UR}^{tc})^4$ .

Figs.(3,4,5) show the cross section of  $pp \rightarrow tt\bar{c} + X$  as a function of  $m_{\pi_t^0}$  for various  $K_{UR}^{tc}$  and  $m_{h_t}$ . The charge conjugate production  $pp \rightarrow \bar{t}t\bar{c} + X$  is also taken into account. From these figures, one can see that even for  $K_{UR}^{tc} = 0.1$ , the cross section can reach several tens fb in a sound parameter space, and, depending on different parameter space, it may be larger or smaller than the cross section of  $pp \rightarrow tt + X$ . The sharp drops of the cross section at  $m_{\pi_t} \simeq 360$  GeV in these figures reflect the suppression of  $Br(\pi_t^0 \rightarrow t\bar{c})$  due to the opening of decay channel  $\pi_t^0 \rightarrow t\bar{t}$ . Like Fig. 2, the dip of the cross section around  $m_{\pi_t} = 300$  GeV in Fig. 4 is due to the cancellation effects of top-pion and top-higgs diagrams.

The signature of  $pp \rightarrow tt\bar{c} + X$  is two like-sign dileptons, two b-jets, one light quark jet plus missing energy, i.e.,  $\ell^+\ell^+bbj_1 + \cancel{E}$  ( $\ell = e, \mu$ ). The background is mainly from  $pp \rightarrow W^+t\bar{t} \rightarrow \ell^+\ell^+bbj_1j_2 + \cancel{E}$  with either  $j_1$  or  $j_2$  missing detection. If we require exactly three jets with at least one b-jet in the signal events, then according to Fig.9 of Ref. [10], about 3/4 of the background can be cut out so that  $\sigma(Wt\bar{t}) < 100$  fb. The ratio of signal to background can be further enhanced by applying appropriate kinetic cuts [10]. So the signal with a rate large than several tens of fb should be observable at the LHC.

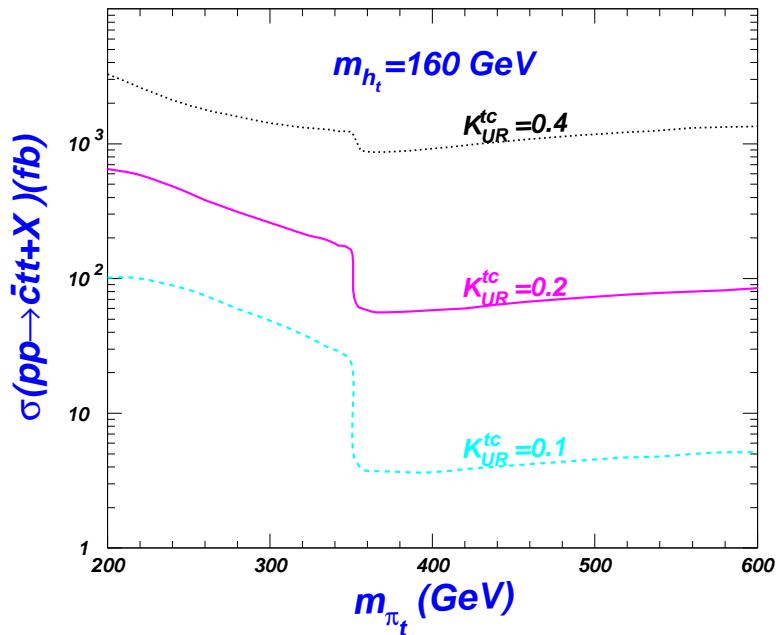


FIG. 3. Cross section of  $pp \rightarrow tt\bar{c} + X$  at the LHC as a function of  $m_{\pi_t}$  for various  $K_{UR}^{tc}$ .

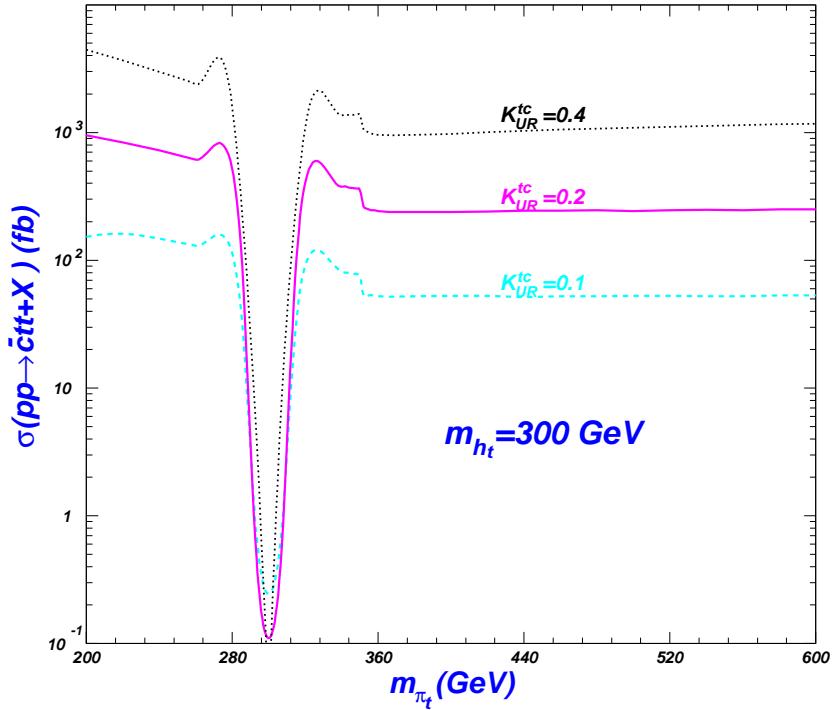


FIG. 4. Same as Fig.3, but for  $m_{h_t} = 300$  GeV.

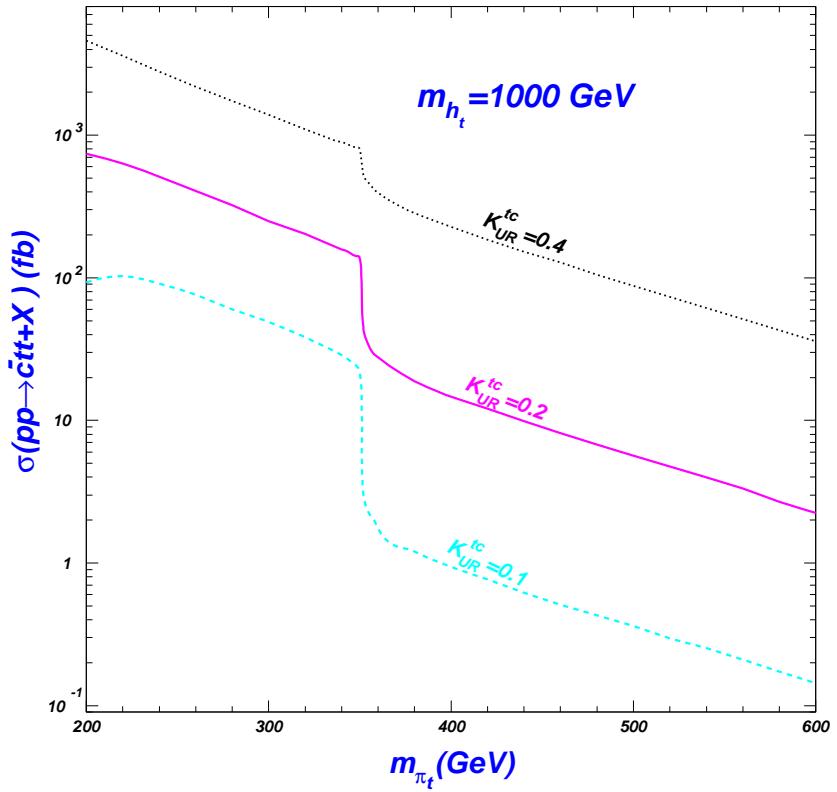


FIG. 5. Same as Fig.3, but for fixed  $m_{h_t} = 1000$  GeV.

A contour of the cross section in the  $K_{UR}^{tc}$ - $m_{\pi_t}$  plane is plotted in Fig.6. The region above each curve corresponds to a cross section larger than 10 fb. We see that in a large part of parameter space the cross section can exceed 10 fb for both processes.

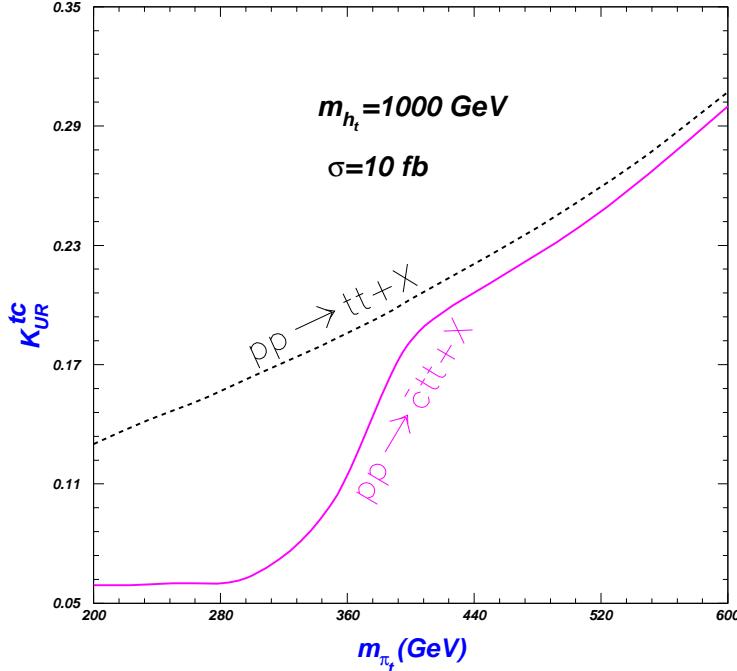


FIG. 6. The contour of the cross section for  $pp \rightarrow tt + X$  and  $pp \rightarrow tt\bar{c} + X$  at the LHC in  $m_{\pi_t}$ - $K_{UR}^{tc}$  plane.

We would like to make some comments on other like-sign top pair production processes. First, we take a look at the production  $pp \rightarrow tt\bar{c}q + X$ , as shown in Fig.1 (e,f). At first glance, this production may also have a sizable rate. However, as found in the literature [11,19,36], due to the unitary constraint, there exists severe cancellation between different diagrams so that its rate is highly suppressed. We have calculated this process and found that the cross section can maximally reach several tens fb. But the background  $t\bar{t}W^+$  in Eq.(11) is quite severe for this production. So it is not as powerful as  $tt$  and  $tt\bar{c}$  productions in probing the TC2 theory. The production  $pp \rightarrow t\bar{t}\pi_t^*(h_t^*) \rightarrow tt\bar{c}$  [19] can also lead to like-sign top pairs in the final state at the LHC. But analyzing its signal and background is quite complicated due to the multi particles in the final state. Particularly, if we require the two like-sign top quarks to decay semileptonically, the reconstruction of this process may be quite difficult. We do not perform further analysis about these processes.

Before ending this section, we want to point out that the like-sign top pair productions may be quite unique in probing the TC2 model at the LHC. To enhance the like-sign top pair production rate to the accessible level at the LHC, the FCNC top quark couplings  $t\bar{c}\phi$  ( $\phi$  is any scalar field) or  $t\bar{c}V$  ( $V = \gamma, Z, g$  or any new gauge boson) cannot be too small. The TC2 model predict sizable tree-level  $t\bar{c}\phi$  ( $\phi$  is top-pion or top-higgs) coupling and thus may enhance the like-sign top pair production rate to the accessible level at the LHC. In many other popular extensions of the SM, there are no tree-level top quark FCNC couplings and the couplings  $t\bar{c}\phi$  and  $t\bar{c}V$  are induced at loop-level, which are usually too small to make the like-sign top pair productions observable at the LHC. For example, the top quark FCNC couplings are induced at loop-level in the MSSM [4]. Although they can be much larger than in the SM, we found that their contribution to the cross sections of  $pp \rightarrow tt + X$  at the LHC is smaller than  $10^{-4}$  fb. Note that among the two-Higgs doublet models, the so-called type-III model (2HDM-III) [37] allows tree-level FCNC  $t\bar{c}\phi$  interactions. However, such couplings are related by the CKM matrix with the flavor-changing charged-Higgs interactions, and thus are severely constrained by low energy data [38]. For the currently allowed parameter space of 2HDM-III, we found that the cross section at the LHC can maximally reach several tens fb for  $pp \rightarrow tt\bar{c} + X$  and 10 fb for  $pp \rightarrow tt + X$ . Such rates just lie on the edge of observation at the LHC. Therefore, the like-sign top pair productions at the LHC cannot constrain the 2HDM-III efficiently.

#### IV. CONCLUSION

The TC2 theory predicts tree-level FCNC top quark Yukawa couplings with top-pions. We examined various like-sign top pair productions induced by such FCNC couplings at the LHC. We found that the productions  $pp \rightarrow tt + X$  and  $pp \rightarrow tt\bar{c} + X$  can reach several tens fb in a sound part of parameter space, which may be observable due to the low backgrounds. Since other popular new physics models like the MSSM cannot enhance these rare productions to the observable level, searching for these productions at the LHC will serve as a powerful probe for the TC2 model.

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